Chapter 4: Material Properties

B. Stark

MEMS are constructed out of a multitude of materials, each of which has unique reliability implications. Different materials have different responses to failure mechanisms that need to be understood to better device reliability. To help clarify the purposes of the myriad of MEMS materials, this chapter offers a brief overview of the materials used in MEMS and provides a listing of their properties.

One of the great debates within the MEMS community has focused upon whether to use the thin film or the bulk properties of materials in performing structural analysis. The problem with treating many of these materials as bulk materials is that, when samples become as small as they do in MEMS, crystal defects are no longer small in comparison to the size of the structure being analyzed. While most testing is performed on macroscopic samples, these properties probably do not scale well enough to be used for MEMS, but are often employed anyway for lack of better numbers. For ultimate reliability statistics to be determined, the actual properties of a given material made on a given process line will have to be characterized. Lacking this, approximations can be made with the available data. This chapter offers the common bulk materials properties that are generally accepted. For thin films the applicability of these properties is still somewhat in doubt.

I. Single Crystal Silicon

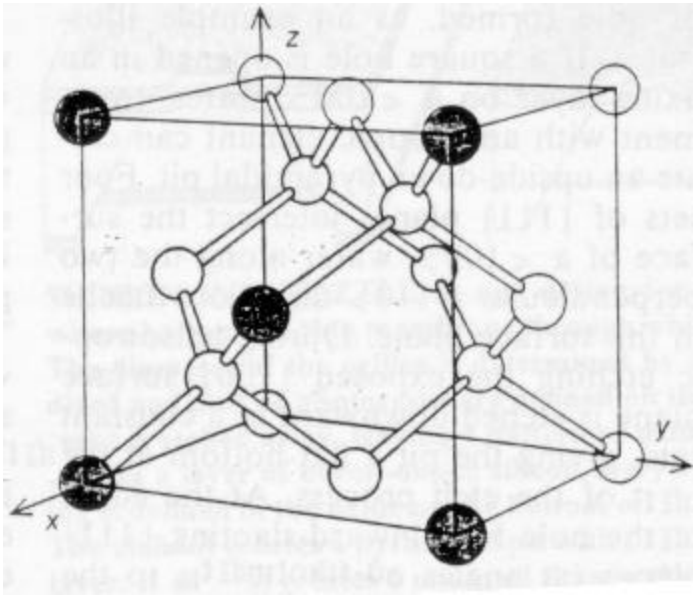
Silicon is the most common material used in semiconductor devices. In crystalline form, silicon aligns in a diamond structure, which consists of a face-centered cubic lattice with a basis of two atoms, as shown in Figure 4-1. The atomic structure of silicon determines many of its physical properties, which are listed in Table 4-1.

Property	Value
Crystal structure	Diamond
Lattice constant	5.43 Å
Atoms/cm^3	5.0×10^{22}
Density	2.32 g/cm^3
Melting point	1412 °C
Specific Heat	.7 J/g-°C
Young's modulus <100>	130 GPa
Stiffness Constants:	
E_{11}	165.6 GPa
E_{12}	63.98 GPa
E_{44}	79.51 GPa
Poisson's ration <100> orientation	0.28
Tensile strength	3790 MPa
Fracture toughness	.9 MPa m^.5
Thermal conductivity	1.5 W/cm-°C
Coefficient of thermal expansion	4.2 x 10^{-6} °C^{-1}
Heat Capacity	20.07 (J/mol-K)
Breakdown Field	~3 x 10^5 V/cm
Piezoresistive coefficients	
n-type: π_{11}	6.6×10^{-11} Pa^{-1}
π_{12}	-1.1×10^{-11} Pa^{-1}
π_{44}	138×10-^{11} Pa^{-1}
p-type π_{11}	-102×10^{-11} Pa^{-1}
π_{12}	53.4×10^{-11} Pa^{-1}
π_{44}	-13.6×10^{-11} Pa^{-1}
DC dielectric constant	11.7
High frequency dielectric constant	11.7
Resistivity	2.3 x 10^5 Ω-cm
Energy Gap	1.12 eV
Electron mobility	1500 cm^2/V-s
Hole mobility	450 cm^2/V-s
Index of Refraction	3.42

Table 4-1: Room-temperature properties of single crystal silicon.[6,17]

As its atomic similarities to diamond might imply, single crystal silicon is a very hard substance. It exceeds the mechanical strength of steel, but is decidedly more brittle. Its strength makes silicon ideal for many MEMS structures, as it has the highest fracture strength of any material commonly used in MEMS. Due to well controlled processes that yield high purity crystalline structures, silicon has the desirable quality that its mechanical properties are very reproducible.[6] For these reasons, silicon is often used for high-quality microstructures.

Figure 4-1: Crystal structure of silicon. (from [96])



The science of silicon growth has developed extensively over the past few years. Silicon wafers are now produced with dislocation densities on the order of .1 dislocations/cm^2, which helps to explain the high fracture strength of the material. These wafers also have impurity densities less than .03 particles/cm^2.

In a diamond cubic lattice, like that of silicon, fracture will normally occur along the {111} planes. This is due to the fact that these planes have the lowest surface energy to resist crack propagation. Although fracture along the other crystal planes is certainly possible, it generally will not occur without the aid of a dislocation to lower its strength.[47]

As technology progresses, the fact that silicon does not have the superior electrical and optical properties of other materials has been a minor drawback. Silicon has a lower electron mobility than some other common semiconductor materials, which impedes high frequency operation. While this is a concern for digital designers, it is of little import to MEMS designers, as there are relatively few applications that need mechanical structures to run at the frequency limits of silicon. On the other hand, the electrical properties of silicon have the advantage that

they are sensitive to stress, temperature, magnetic fields, and radiation, which is a characteristic that has been taken advantage of in a number of solid-state sensors.

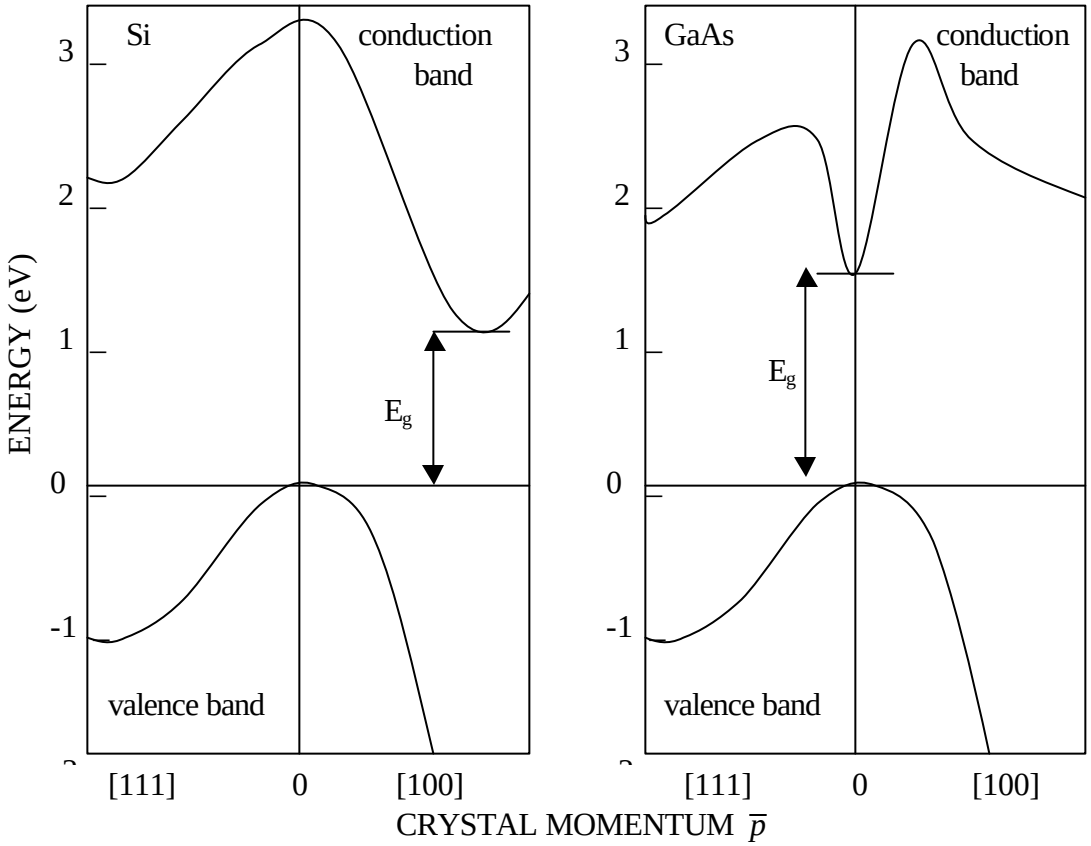


Figure 4-2: Energy band structures of Si and GaAs.

An issue of great importance in silicon is its energy band structure. In the first half of the twentieth century, scientists researching quantum mechanics discovered that electrons in solids can only have discrete energy levels. These energies are separated into distinct bands. At the lowest potential, all electrons in a solid occupy the valence band, which corresponds to the valence orbits in the atoms. After some energy, often in the form of light or heat, has been added to the solid, electrons will transition into the conduction band. The distance between these two energy levels, called the bandgap, determines the fundamental electrical properties of a material. In insulators, such as glass and rubber, the bandgap will be on the order of several electron-volts. Conversely, in good conductors, such as most metals, the bandgap will be less than an electron-volt. Semiconductors occupy the region in between these two areas, with a medium sized bandgap. As such, intrinsic silicon has a moderate resistivity of 2×10^5 Ω-cm.

While the bandgap determines the electrical properties of a device, it also affects the optical properties. The energy level of the valence and conduction bands varies within a semiconductor material. The bandgap is calculated by subtracting the minimum of the

conduction band from the maximum of the valence band. In some materials, such as GaAs, these two points line up. Materials in which this occurs are called direct bandgap semiconductors and have the property that electrons only need to change energy levels to switch band levels, which causes a photon to be emitted when an electron drops from the conduction to the valence band. Materials, like silicon, where this does not occur, are called indirect bandgap semiconductors. Electrons in indirect bandgap semiconductors need to change both momentum and energy to switch band levels, as shown in Figure 4-2.

Thus, intrinsic silicon, as an indirect band-gap material, cannot be used in the production of semiconductor lasers and light emitting diodes. This limitation in silicon has led to research into whole new classes of semiconductor materials that are capable of emitting light.

II. Polycrystalline Silicon

In applications involving surface micromachining, thin films of silicon are needed as a structural material. Since it is difficult to grow thin films of single crystal silicon, thin films of polycrystalline silicon are grown instead.[6] These materials are now finding extensive use in the

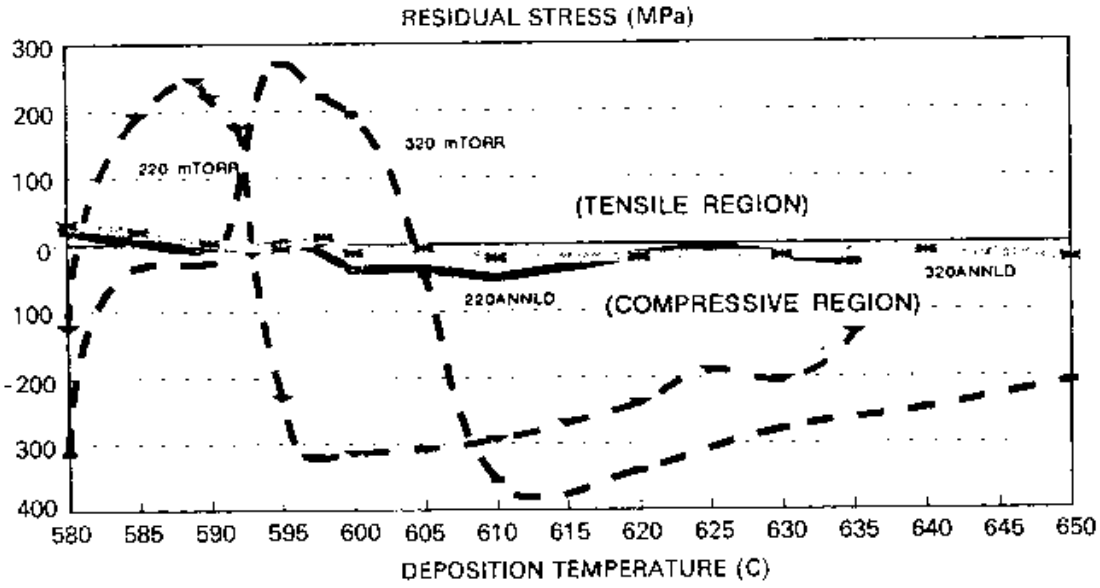


Figure 4-3: Residual stress as a function of deposition conditions. (from [104])

MEMS industry.

The mechanical properties of polysilicon films depends greatly upon the process used in deposition. The residual stress can be controlled almost entirely by varying deposition pressure

and temperature, as shown in Figure 4-3. It has also been discovered that there is a direct link between the presence of <110> oriented grains and residual stress in films, although the reasons for this are not entirely clear.[45]

The strength of polycrystalline silicon is less well understood. Different researchers have reported a Young's modulus ranging between 140 to 210 GPa,[130] with these values having a dependence on crystal structure and orientation. Recent research has shown that the Young's modulus of polycrystalline films is highly dependent upon deposition conditions. The films exhibit preferential grain orientations that vary with temperature. Since an ideal film does not exhibit orientation dependence for its mechanical properties, researchers have found that depositing films at 590 ^{o}C, which is the transition point between polycrystalline and amorphous silicon, is an effective method of producing an isotropic film of polysilicon. At this temperature, the amorphous silicon will recrystalize during annealing, which produces films with a nearly uniform Young's modulus of 165 GPa.

In polycrystalline materials, the fracture strength is dependent upon two factors, the grain size, d, and the fracture surface energy, γ_s. This stems from the fact that the size of a dislocation is usually governed by the grain size, which, by Griffith's equation, shows that the fracture strength of this material is:[103,119]

$$s_f = \sqrt{\frac{4Eg_s}{pd}} \qquad (4\text{-}1)$$

As shown by the equation, the fracture strength is also dependent upon the fracture surface energy, γ_s. For small grained polycrystals, the energy needed to fracture a grain surface increases with grain size.[44] As a result, larger grains will be stronger due to the increased energy needed to propagate a crack across the material.

In several studies, the mean fracture strength of polysilicon has been found to be between 2 to 3 GPa, which is clearly less than that of single crystal silicon. Polysilicon fracture samples have been reported to have a Weibull modulus similar to that of single crystal silicon, which would indicate a similar reliability of the two materials.[40,44,103]

III. Silicon Dioxide

Silicon dioxide is commonly used as an insulator in integrated circuits. In MEMS it is used to electrically isolate components and has been used in some recent applications as a structural material.[7] Its basic properties are listed for reference in Table 4-2.

Property	Value
Density	2.65 g/cm^3
Melting point	1728 °C
Young's modulus	66 GPa
Tensile strength	69 MPa
Thermal conductivity	1.4 x10^{-2} W/°C-cm
Thermal coefficient of expansion	7 x 10^{-6} °C^{-1}
Dielectric constant	3.78
Resistivity	10^{12} Ω-cm
Energy gap	8 eV
Index of refraction	1.46

Table 4-2: Room temperature properties of silicon dioxide.[85]

In the crystalline form of Quartz, silicon dioxide exists in the trigonal trapezohedral class of the rhombohedral system. This class has one axis of three fold symmetry and three polar axes of two-fold symmetry. Quartz, due to its high piezoelectric coupling, is occasionally used in MEMS. However, as a result of its high anisotropy, quartz is more difficult to etch than silicon.[124,125]

Silicon dioxide is a common component of glasses and is, as such, a very weak and brittle material. Thin films of oxide have a compressive internal stress on the order of 1 GPa. Despite this, due to the fact that silicon dioxide is less stiff than other thin film materials and that it has unique electrical properties, it is occasionally used as a mechanical material in high sensitivity applications. Silicon dioxide, with its low thermal conductivity, is a natural thermal insulator, a property which has been exploited for the production of integrated thermal detectors. With a low tensile strength, silicon dioxide is susceptible to mechanical fracturing.

One major feature of silicon dioxide is its properties as an insulator. With a bandgap of 8 eV, silicon dioxide can effectively separate different layers of conductors with little electrical interference. Due to the inherent advantages in being able to integrate such an effective insulator, silicon dioxide has helped to make silicon the semiconductor material of choice for most applications.

IV. Silicon Carbide

In recent years there has been a growing interest in the use of silicon carbide as a material for MEMS. SiC has many properties that make it well suited for MEMS applications, although the SiC wafer growth technology has not matured enough to make it a common MEMS material. Polycrystalline silicon carbide exists in about 180 different polytypes, with the four dominant structures listed in Table 4-3.

Modification	Polytype
α-SiC	6H
(High-temperature modification)	15R
	4H
β-SiC	
(Low-temperature modification)	3C

Table 4-3: Dominant SiC types.[112]

Due to the fact that SiC exists in its beta form at temperatures below 2000 ^{o}C, this is called its low-temperature modification. Above this temperature, only hexagonal and rhombohedral polytypes are stable.

The properties of SiC are highly dependent upon the processing conditions and can vary quite dramatically. These properties are listed for a few different SiC preparation techniques.

SiC type	SiC content	Density (g/cm^3)	Young's modulus (GPa)	Thermal expansion coefficient (10^{-6} ^{o}C^{-1})	Thermal conductivity (W /m-K)	Flexural strength (MPa)
Ceramic bonded	up to 95%	2.55	100	5.8	16	30
Recrystallized	100%	2.55	240	5.0	28	100
Sintered	95%	2.55	410	4.9	50	450
Hot-pressed	98%	2.55	450	4.5	55	650

Table 4-4: Room temperature properties of SiC.[112]

While not all of these methods are compatible with wafer growth, it should be apparent that the properties of SiC can vary significantly depending upon processing.

Silicon carbide is used for its extreme hardness and high temperature resistance. SiC does not have a defined melting point, instead it has a breakdown point of 2830 ^{o}C. At this temperature, SiC decomposes into graphite and a silicon rich-melt. Many SiC structures are less elastic than silicon, which is useful in certain MEMS applications. SiC also has a Poisson's ratio that varies between .183 and .192. The main drawback to SiC in MEMS has been that the

technology used to grow SiC wafers still results in high dislocation densities. This lowers the strength of SiC, which prohibits its use in many applications. For silicon carbide to find widespread use, the techniques used to manufacture it must continue to mature.[112,113]

Silicon carbide, with a band-gap around 3eV, is a wide-bandgap semiconductor material. While the exact width of the bandgap depends on the polytype, SiC is a better natural insulator that Si or GaAs. Intrinsic SiC has a resistivity of 10^8 Ω-cm, although doping can vary this value from .1 to 10^{12} Ω-cm. Silicon carbide also oxidizes readily above 600 °C to form silicon dioxide by the reaction:[112]

$$SiC + 2O_2 \rightarrow SiO_2 + CO_2 \qquad (4\text{-}2)$$

V. Silicon Nitride

Silicon nitride is a material that is employed in a variety of applications. Since it does not react well with many etching solutions, silicon nitride is often used to prevent impurity diffusion and ionic contamination. Its basic properties are listed in Table 4-5.

Property	Value[1]
Density	3.1 g/cm^{-3}
Melting point	1900°C
Young's Modulus	73 GPa
Fracture strength	460 MPa
Coefficient of thermal expansion	3×10^{-5} °C^{-1}
Thermal conductivity	0.28 W /cm-°C
Resistivity	10^{15}Ω-cm
Dielectric constant	9.4
Breakdown field	1×10^{7} V/cm
Index of refraction	2.1
Band gap	3.9-4.1 eV

Table 4-5: Room temperature properties of silicon nitride.[18]

The silicon nitride films used in most MEMS devices are amorphous and are usually either sputtered or deposited by CVD. These films are made with the following reaction, which occurs between 300-500 mT and 700-900°C.

[1] Varies with processing conditions.

$$3SiH_2Cl_2(g) + 4NH_3(g) \xrightarrow{heat} Si_3N_4(s) + 6HCl(g) + 6H_2(g) \quad (4\text{-}3)$$

Stoichometric nitride films have tensile stresses on the order of 1-2 GPa, which causes large warping. To maintain the structural integrity of the films, they are usually only grown a few hundred nanometers thick. To avoid this limitation, silicon-rich nitride films are often used. A common film of $Si_{1.0}N_{1.1}$ has been developed that has a Young's modulus on the order of 260-330 GPa, a Poisson's ratio of 0.25, and a fracture strain on the order of 3%.[45]

The stress of silicon nitride films can be controlled simply by adjusting the deposition temperature and the ratio of dichlorisilane to ammonia. As shown in Figure 4-4, nearly zero stress films are grown with a ratio of 4:1 at a temperature of 835 °C.

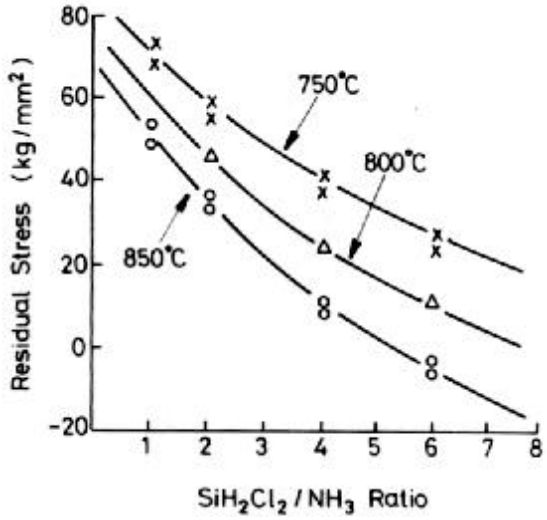


Figure 4-4: Residual stress in silicon nitride films as a function of processing conditions. (from [105])

Silicon nitride has many mechanical properties that make it a desirable material to work with. It is a better thermal insulator than polysilicon, which can be important for isolating surface micromachined structures. Also, its high mechanical strength makes it an ideal film for friction and dust barriers.

One of the unfortunate properties of silicon nitride is that it is not as good an insulator as silicon dioxide. With a bandgap 40% smaller than SiO_2's, the electrical isolation provided by silicon nitride is significantly less than that of silicon dioxide. Furthermore, Si_3N_4 forms a low energy barrier towards silicon and metals, which facilitates the injection of holes into the dielectric at electric fields greater than 2×10^6 V/cm. This results in a hysteresis appearing in the capacitance-voltage curve of metal-insulator-semiconductor structures after the voltage has been swept to large values. Due to these concerns, some designers like to form most of an insulator with SiO_2 and then seal its surface with Si_3N_4.[18]

VI. Gallium Arsenide

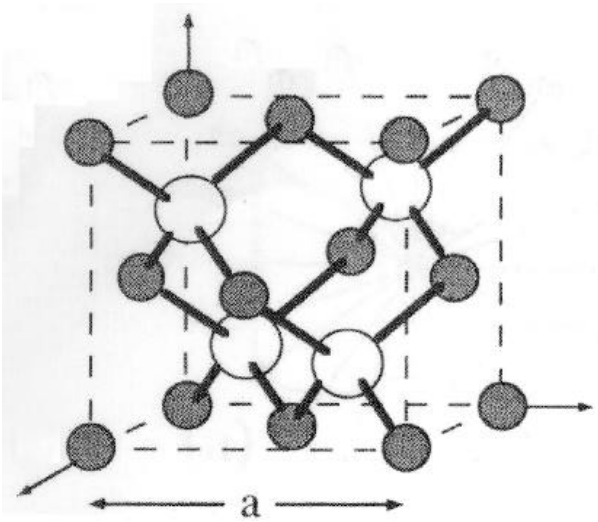


Figure 4-5: Crystalline gallium arsenide. (from[17])

Gallium arsenide is the second most common semiconductor material. It has some unique properties that make it ideal for use in applications that silicon is ill-suited for. Initially finding a niche in the Monolithic Microwave Integrated Circuit market, gallium arsenide, due to its optical properties, has recently been used in the production of optical MEMS, or OMEMS.

Gallium arsenide forms a face centered cubic lattice with a basis of one gallium and one arsenic atom in what is called a zincblende structure, as shown in Figure 4-5. The basic material properties of gallium arsenide are listed in Table 4-6.

Property	**Value**
Crystal structure	Zincblende
Lattice constant	5.65 Å
Atoms/cm^3	4.42 x 10^{22}
Density	5.32 g/cm^3
Melting point	1237 °C
Specific heat	.35 J/g-°C
Young's modulus <100> orientation	85.5 GPa
Stiffness constants:	
E_{11}	118.8 GPa
E_{12}	53.8 GPa
E_{44}	58.9 GPa
Poisson's ratio <100> orientation	0.31
Fracture toughness	.44 MPa m^.5
Thermal conductivity	.46 W/cm-°C
Coefficient of thermal expansion	6.86 x 10^{-6} $°C^{-1}$
Heat capacity	47.02 J/mol-K
Breakdown Field	~4 x 10^5 V/cm
DC dielectric constant	13.18
High frequency dielectric constant	10.89
Resistivity	10^8 Ω-cm
Energy Gap	1.424 eV
Electron mobility	8500 cm^2/V-s
Hole mobility	400 cm^2/V-s
Index of Refraction	3.66

Table 4-6: Room temperature properties of gallium arsenide.[6,17]

AlGaAs has also become an integral part of GaAs processing. New technologies have started to use this ternary compound in GaAs based MEMS systems. AlGaAs is an attractive compound because it exhibits many properties that complement GaAs:

Property	Value
Crystal structure	Zincblende
Lattice constant	5.66 Å
Atoms/cm^3	4.42 x 10^{22}
Density	3.76 g/cm^3
Melting point	1467 °C
Specific heat	.48 J/g-°C
Stiffness constants:	
E_{11}	120.2 GPa
E_{12}	57.0 GPa
E_{44}	58.9 GPa
Fracture toughness	1.7 MPa m$^{-.5}$
Hardness	5 GPa
Thermal expansion coefficient	5.2*10^{-6} ºC^{-1}
Thermal conductivity	.9 W/cm-^{o}C
DC dielectric constant	10.06
High frequency dielectric constant	8.16
Energy Gap	2.168 eV (indirect)

Table 4-7: Room temperature properties of AlAs.[17]

Gallium arsenide is not used in the semiconductor industry for its mechanical characteristics. While sharing many of the same mechanical properties of silicon,[6] it is significantly weaker, with its Young's modulus only 54% that of silicon. It, like silicon, is also very brittle and thus offers no advantages in terms of mechanical performance.

GaAs contains more crystal defects than high quality silicon and, of these, arsenic precipitates are of paramount importance in determining fracture strength. For a normal distribution of arsenic precipitates in a large sample, such as a wafer, there will always be at least one defect large enough to cause small load fracturing. However, for small samples of materials, it is quite common to have limited defect size, which allow the manufacture of high stress structures out of macroscopically low stress materials.[17]

Due to the fact that GaAs is not an elemental structure, it exhibits some mechanical properties that would not be expected from other materials. In GaAs, the electron cloud tends to shift towards the arsenide atoms, which creates a dipole moment along the [111] axis. This causes the eight {111} surfaces to have differing concentrations of Ga and As atoms. As a

result, the {111} planes are much tougher than expected. This toughening causes the {110} planes to be the primary fracture points.[17]

Gallium arsenide also has a thermal conductivity that is less than one-third that of silicon and one-tenth that of copper, which makes it a poor conductor. The consequence of this poor conductivity is that the packing density of GaAs devices is limited by the thermal resistance of the substrate. Another thermal concern is the fact that brittle materials becomes ductile at around 35% of the melting point. Corresponding to 250 °C in GaAs, this marked drop in hardness and increase in fatigue could present serious problems for high temperature device operation.

Gallium arsenide finds most of its applications due to its superior optical and electrical properties. As shown in Tables 4-1 and 4-6, GaAs has close to six times the electron mobility of silicon. Electron mobility, which describes how strongly an electron is influenced by an electric field, is derived from the laws of basic physics and is related to Equation 4-4:

$$v_d = -\left(\frac{qt_c}{m^*}\right)E \tag{4-4}$$

where:

v_d = drift velocity

q = electron charge

t_c = mean free times between collisions

m* = effective electron mass

E = electric field

In Equation 4-4, the bracketed proportionality constant is called the electron mobility. As the equation clearly indicates, electron mobility is directly proportionate to the mean free time between collisions, t_c. This number is in turn a function of the lattice and impurity scattering of electrons. The lattice scattering is a result of thermal vibration and increases with temperature until it becomes the dominant factor, as impurity scattering is a constant function of doping levels. Thus, the electron mobility is a function of temperature, which changes based on the intensity of device operation. As a result of this, the electron mobility of GaAs is not always six times that of silicon, as it may often only be double that of silicon.[1]

With the electron mobility determining maximum operating frequency and with GaAs always having a greater electron mobility than silicon, GaAs can operate at higher frequencies than silicon, which has made it an ideal material for many communications applications. However, for MEMS, these factors are limited in their import. While some high frequency GaAs systems are attempting to integrate MEMS components, most GaAs MEMS devices will operate at significantly lower frequencies due to the mechanical limitations of the systems.

Gallium arsenide also has a larger energy band gap than that of silicon, which means that it is a better natural insulator. Through the introduction of either oxygen or chromium to the GaAs melt, it can further be turned into a semi-insulating material. This provides a substrate that isolates components and performs many of the same tasks, albeit not as effectively, as silicon dioxide.

The other significant advantage that GaAs has over silicon is that it is, as discussed previously, a direct band gap semiconductor material. This has enabled whole classes of optomechanical devices to be developed. It is this property that allows semiconductor lasers and LEDs to be made out of GaAs and it will undoubtedly be exploited more in the future.

While gallium arsenide does have significant advantages over silicon there are also some major drawbacks. There are no stable insulating oxides and nitrides in GaAs technology. This means that it is difficult to manufacture reproducible passivation layers.

VII. Metals

Metals are used in MEMS as electrical conductors and occasionally as structural material. The metals used in MEMS are, unlike the materials discussed previously, ductile. That means that they will plastically deform if stressed past the yield strength. Plastic deformation results in a non-zero strain with zero applied stress, which appears as a shift in the stress strain curve, as shown in Figure 4-6.

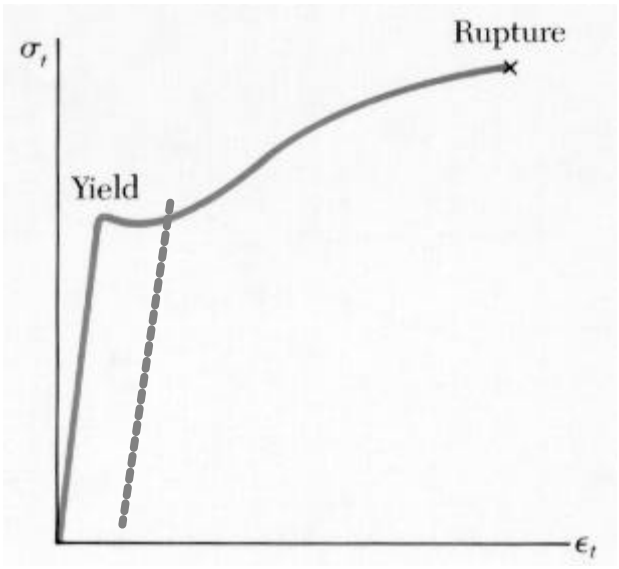


Figure 4-6: Stress versus strain curve for a ductile material. There is a clearly marked yield point, after which plastic deformation occurs. If the material is stressed past this point and then unstressed, the curve will decrease parallel to the elastic deformation section, as illustrated by the dotted line.

A. Aluminum

Aluminum is commonly used in MEMS as a sputtered film placed over a processed structure. By covering a structure with a conductive film, equipotential surfaces are created on a device, which are critical to the operation of many electrostatic device. Aluminum is also commonly used as an electrical conductor in semiconductor technologies.

Aluminum, like most metals, is often alloyed with other substances to improve its structural properties. The alloys of aluminum are numerous and are offered in great detail in Reference [111]. Pure aluminum has many properties that distinguish it from other materials used in MEMS. Listed in Table 4-8, the properties of aluminum have been both a boon and an area of concern for researchers over the past decades.

Property	Value
Density	2.71 g/m^3
Melting Point	659^{o}C
Specific Heat	0.90 J/g-^{o}C
Young's modulus (bulk value)	70 GPa
Poisson's ratio	.35
Ultimate tensile strength	110 MPa
Ultimate shear strength	70 MPa
Yield tensile strength	100 MPa
Yield shear strength	55 MPa
Thermal conductivity	2.37 W/cm-^{o}C
Coefficient of thermal expansion	23.6×10^{-6} ^{o}C^{-1}
Resistivity	2.82×10^{-6} Ω-cm

Table 4-8: Room temperature properties of 99.6% pure aluminum.[46,101,111]

The mechanical properties of aluminum are considerably poorer than Si and GaAs. With a Young's modulus that is less than half that of silicon, it is clearly a more ductile material. However, since the yield strength of aluminum, at 100 MPa, is at least an order of magnitude below the fracture strength of Si and GaAs, aluminum is rarely used as a structural support in MEMS.

For a considerable amount of time, aluminum was the only good conductor that could easily be integrated into ICs. Since aluminum forms Al_2O_3 bonds with SiO_2, it is simple to adhere it to passivation layers. This fact lead to its widespread implementation, despite the fact that materials existed with better electrical properties.

B. Gold

Gold is a substance that is finding increasing use in the MEMS field. While not as common as aluminum, it has many of the same features with some added advantages. Its properties are listed below for reference.

Property	Value
Density	19.3 g/m^3
Melting Point	1063^{o}C
Specific Heat	0.13 J/g-^{o}C
Young's modulus (bulk value)	75 GPa
Poisson's ratio	.42
Ultimate tensile strength	125 MPa
Thermal conductivity	3.15 W/cm-^{o}C
Coefficient of thermal expansion	14.2×10^{-6} ^{o}C^{-1}
Resistivity	2.44×10^{-6} Ω-cm

Table 4-9: Properties of gold[46,102,111]

Gold is not a material known for its strong mechanical properties. It is a soft, ductile material that is easily deformed. As a result, it is not used as structural material. Instead, it will almost always be layered on top of a more rigid material or be used in applications that do not require mechanical motion. Gold does have problems adhering to SiO_2, but there are some established methods to circumvent them. One method employed is to use an intermediary layer of chromium as an adhesive, since it forms Cr_2O_3 with SiO_2 and also strongly bonds to gold.

The main impetus for the use of gold in MEMS applications has been the fact that it is a better electrical conductor than aluminum. In applications where high conductivity is of paramount importance, gold is often the material of choice. One of the attractive properties of gold is that it is a fairly inert material. This means that its surface does not readily oxidize in atmosphere, which helps to maintain its conductivity in atmospheric applications.

C. Copper

With the recent integration of copper into ICs, it will only be a matter of time before copper becomes integrated into MEMS. Since many designers hope to eventually place MEMS in system-on-a-chip devices, it is of paramount importance that low power systems, that must therefore employ copper, can be developed. Copper has some unique properties that make it worth the effort to integrate, as shown on the following page.

Property	Value
Density	8.89 g/m^3
Melting Point	1083^{o}C
Specific Heat	0.39 J/g-^{o}C
Young's modulus (bulk value)	115 GPa
Poisson's ratio	0.36
Ultimate tensile strength	220 MPa
Ultimate shear strength	150 MPa
Yield tensile strength	100 MPa
Thermal conductivity	3.98 W/cm-^{o}C
Coefficient of thermal expansion	16.6×10^{-6} ^{o}C^{-1}
Resistivity	1.72×10^{-6} Ω-cm

Table 4-10: Properties of 99.99% copper.[46,101,111]

Copper is actually a slightly stronger material than pure aluminum. However, it is unlikely to be used as anything but a conductor in the near future due to the fact that it does not adhere especially well to silicon, which makes it likely to delaminate. The ability of copper to find a niche in the MEMS community will largely hinge upon the strength of the adhesive bonds that can be formed. Copper is an excellent thermal conductor, which will prove useful in many applications.

The main reason that large investments have been made into the development of copper in ICs and MEMS is that it has a higher conductivity than aluminum and gold. This means that it will dissipate lower amounts of heat and waste less power. Thus, there is a great incentive to integrate copper into the MEMS industry in general and in the space MEMS industry in particular.

VIII. Polyimides

Polyimides are a class of organic films that have proven promising as a possible replacement for SiO_2 as an insulator in microelectronics. There are a number of different commercially available polyimide films used in the semiconductor industry and their properties vary significantly. The main reason for the investigation of polyimide films is that they offer a new generation of low permittivity dielectrics, some of which have been reported to have a permittivity of less than $2\varepsilon_0$. Since lower dielectric constant insulators dissipate less power in FETs, these materials may begin to find their way into the MEMS community. The materials properties of a PMDA/BPDA/TFMOB polyimide film have been fairly well investigated and are offered below.

Property	Value [1]
Young's Modulus (in plane)	7.5 GPa
Young's Modulus (out of plane)	8.0-15.0 GPa
Shear Modulus	1.0-10.0 GPa
Poisson's Ratio(in plane)	0.35
Poisson's Ratio (out of plane)	0.1-0.45
Dielectric coefficient	2-4
Coefficient of thermal expansion	6.0×10^{-6} C^{-1}

Table 4-11: Properties of PMDA/BPDA/TFMOB polyimide.

Polyimides are a weak class of materials. Their main function in MEMS has been in circuits and as a layer of chemically active sensor materials on membranes and cantilevers. As such, polyimides are generally not considered for structural applications.

The main impetus for developing polyimides was that they could have a lower dielectric constant than SiO_2, which could represent a major reduction in power consumption on integrated circuits. Thus, much like copper, polyimides are likely to find introduction into the MEMS market through their inclusion in the consumer electronics market. As good insulators, polyimide films have a myriad of possible uses in the semiconductor industry.

IX. Additional Reading

Michelle M. Gauthier, Engineering Materials Handbook ASM desk edition. Materials Park, OH, November 1995.

K. Hjort, J. Söderkvist and J. -Å. Schweitz, "Gallium Arsenide as a Mechanical Material" *Journal of Micromechanics and Microengineering*, Vol. 4, No. 1, 1994.

D. Bloor, R. J. Brook, M. C. Flemings and S. Mahajan, eds. The Encyclopedia of Advanced Materials, Elsevier Science, Ltd., New York, 1994.

[1] These values will vary by manufacturer.